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AIRPLANE BALANCE.

By

L. Huguet.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

TECHNICAL NOTE NO. 51.

A I R P L A N E B A L A N C E.

By

L. Huguet.

Relative Influence of the Various Constituent Elements of an Airplane on Longitudinal Stability in Flight.

The position of the center of gravity has a preponderating influence on the longitudinal stability of an airplane in flight. Constructors have long been aware of this influence, and, nevertheless, many of them are still content to apply empirical rules to the balancing of their machines.

The results thus obtained are usually very unsatisfactory, corresponding, moreover, to the rules applied. Only those experienced in Aviation, those who have had the opportunity of making many tests and who are capable of drawing correct conclusions from their numerous experiments - only such men can work with any certainty. Others are, for the most part, content either to apply a vague, general law, or to balance their machine for a particular case of flight. In the latter case, they place the center of gravity in a position compatible with that of the resultant of the actions of the air on the cellule, and even such resultant is very vaguely defined by the polar of the wing utilized.

Balance obtained under such poor conditions is rarely satisfactory. The maneuverability of such machines is rarely all that could be desired. In order to improve it, the constructor makes slight changes here and there, he alters the tail, the position of the planes, etc., but, just as vagueness reigned in defining the center of gravity, so these modifications are determined more by guesswork than by logic.

The problem of balance may, however, be discussed.

The metacentric curves given in the Laboratory have already enabled various authors to take up this discussion.

We are generally led to define the rules of balance through our search for the conditions of longitudinal stability of the airplane. As we shall see further on, the application of these rules nearly always involves recourse to wind tunnel tests, the only tests which enable us to find the laws characterizing the equilibrium of the glider.

The lines of the following discussion were suggested by the very interesting system of curves which the Schneider Works recently had drawn up by the Eiffel Laboratory for the glider corresponding to the all-metal machine of 9 tons which that firm is now making. This system of curves was drawn up as the result of investigations on the balance of machines presented to the S.T.Ae. and which, in free flight tests, were found to be wanting in controllability.

The Laboratory was requested to make experiments on a reduced model for the purpose of determining, for this glider, the displacement curves of the center of total thrust when the angle of attack of the cellule varies and when the setting of the tail varies.

These experiments are, first, of theoretic interest, for the curves obtained enable the fundamental problem of longitudinal stability to be discussed in a very satisfactory fashion.

They are also of great practical interest, seeing that the results furnished agree almost perfectly with those previously noted in free flight tests of modern machines.

Also, by the wind tunnel test of the reduced model they supply the means of determining whether the full sized airplane is well balanced, whether the tail surfaces are sufficient, well placed and efficient.

Actually, an airplane is said to be well balanced when its center of gravity is from 1/3 to 1/4 forward on the chord of the straight-edged cellule which is equivalent to the cellule of the airplane.

The results of the above mentioned experiments are in agreement with this rule, though they show its insufficiency.

They also show the advantages and disadvantages of placing the center of gravity further forward or backward on the wing.

The tunnel tests were carried out as follows:

A complete glider with its tail surfaces was placed in the airstream of the tunnel. The horizontal surfaces consisted of a fixed plane, HAVING ITS CHORD PARALLEL TO THE WING CHORD, and a movable plane (the elevator). These WERE OF SYMMETRICAL PROFILE.

The displacement curves of the center of thrust for the whole of the glider were plotted for different constant settings, α, of the elevator, as function of the angles of attack of the cellule.

There is a curve for each angle α.

The system of curves has the general sweep shown in Fig. 1, where the angles of attack (i) are laid off as ordinates; the distances from the center of thrust to the leading edge of the wing are laid off as abscissas and estimated in % of the chord of the wing.

Each curve of displacement of the center of thrust is defined by the α of the setting.

The angle α of the elevator is measured from a direction parallel to the chord of the wing: it is reckoned as positive above the chord (a setting which makes the airplane dive) and negative below.

The point whose displacement we are studying and which we call conventionally the center of thrust is not a metacenter, but simply the point at which the resultant of the actions of the air intersects the axis of thrust of the propeller.

The position of this point for a given angle α and angle of attack i, will be the abscissa of the point of this curve α, the ordinate being i.

For a clear understanding of the following discussion it must not be forgotten that we always assume the total resultant of the actions of the air to be decomposed into two forces (Fig. 3):

One, along the axis of thrust of the propeller and opposed to the thrust; the other vertical, directed in the sense opposed to the action of gravity.

The following discussion bears upon the curves obtained for this special glider, but the conclusions drawn are of general application, for all the gliders of the usual machines of today are of the same kind and give rise to similar systems of curves.

These curves may vary in form, distance, and position, as we shall see, but such variations do not at all change the conclusions derived from the discussion.

Besides the fundamental test which serves as a basis for this study, other tests have been made on the same glider with tails of varying shapes and dimensions; further on we shall see what interest such tests present.

For the present we will only study from a statical point of view, in the case for which a uniform and rectilinear regime of flight is established, the equilibrium of the forces entering into play and determine the conditions under which the equilibrium considered will be stable, deducing, if possible, from such conditions the precautions to be taken in constructing machines in order to ensure their being stable and manageable.

We will examine the following points:

1st. The longitudinal stability, in flight, of a glider with coinciding centers, assuming that we have a power such that we can always by the thrust of the propeller, balance the component of the forces opposed to thrust.

2nd. The influence exercised on the stability of flight by the position of the axis of thrust with respect to the center of gravity and the whole of the glider.

3rd. Stability on the ground before taking off, and the influence of the position of the landing gear.

4th. The influence of the elements of the glider on the balance, the possibility of sometimes correcting defective balance, and the valuable information given on this point by wind tunnel tests.

5th. A brief examination of the equilibrium of power in horizontal flight, where the conditions of stability peculiar to this kind of flight are added to the previously existing conditions of the stability of the glider, and interfere in fixing the safety limits of certain evolutions.

1st. LONGITUDINAL STABILITY OF THE GLIDER WITH COINCIDING CENTERS.

We shall first discuss the longitudinal stability of the glider on the assumption that the airplane has coinciding centers; that is, that its center of gravity is on the axis of thrust of the propeller.

In this case, according to the decomposition of the forces already considered, only the resultant of lift can affect the longitudinal stability of the machine (Fig. 4).

We shall further assume that there is always a regime of flight established such that (Fig. 5) the component P will be equal to the weight π and T (propeller thrust) will be equal and opposed to T_r (resistance to thrust). For the moment we shall not take into account the magnitude of the relative speed which we shall assume to be always such that the component of lift will balance the weight π.

CONDITION OF BALANCE. - For the machine to be balanced, the center of thrust must be on the vertical through the center of gravity.

It is very clear on Fig. 1 that, for a given angle of attack and a given center of gravity, G, of the glider, balance is only possible for one clearly defined setting of the elevator.

For a given setting of the elevator and a given angle of attack, balance only occurs if the center of gravity occupies a clearly determined position.

For instance, the point g, corresponding to $\alpha = -5^{\circ}$ and $i = +5^{\circ}$, defines a state of equilibrium for the center of gravity G.

REGION OF STABILITY. - In the whole region comprised between oy and o'y' for which oo' is almost 1/3 of the chord of the wing, the positions of equilibrium correspond to stable equilibriums, whatever be the angle of attack.

The position of equilibrium characterized, say, by Gg is stable. In point of fact, to each accidental variation, + di or - di, of the angle of attack i, corresponds a displacement of the center of thrust gg' or gg", such that the thrust gives rise to a torque, correcting, in each case, the accidental deviation, without the pilot having to interfere or change the setting α of his elevator.

Point g', corresponding to an increase in the angle of attack, is in the rear of G, and therefore the corresponding thrust tends to make the machine nose-heavy so long as g' has not returned to the vertical of G.

On the contrary, g", corresponding to a decrease of the angle of attack, is in front of G, so that the thrust tends to make the machine tail-heavy.

REGION OF NEUTRAL EQUILIBRIUM. - On Fig. 1 there is a curve $\alpha = 0^{\circ}$, a flattened curve of vertical inflexion, coinciding with o'y'.

If we assume the center of gravity of the airplane to be at O' and the elevator set at the angle $\alpha = 0^{\circ}$, the machine will be balanced for all angles of attack comprised between 7° and 1°.

This shows that at small angles of attack, the airplane will be balanced with a suitable position of the center of gravity and a given setting of the tail, at any angle of attack within the given limits.

At large angles of attack, for the same position of the center of gravity, balance is assured with tail settings of large absolute value, and we see on the α curves that equilibrium again becomes stable.

REGION OF UNSTABLE EQUILIBRIUM. - We shall now suppose the center of gravity to be situated to the left of o'y' at G_1. At small angles of attack there is for a setting α of the elevator, a position of equilibrium characterized by a point on the curve α, say g_1.

This position of equilibrium is unstable.

In fact, to an accidental increase, + di, of the angle of attack, corresponds a displacement g_1, g'_1 of the center of thrust, and the resulting torque tends to make the machine still more tail-heavy.

If the pilot keeps the elevator setting fixed, the nose of the machine will rise until g'_1 returns to g''_1 above g_1, where equilibrium is stable.

To an accidental dacrease - di of the angle of attack, corresponds a displacement g_1 g''_1 of the center of thrust, and the resulting torque tends to further increase the nose-heaviness of the machine; the equilibrium is no longer stable, for at g^{iv}_1 below g_1, the equilibrium is also unstable.

Thus, for an airplane balanced too much to the rear, equilibrium is only stable at large angles of attack of the cellule.

At large negative angles of attack, balance would only be stable if we considered a regime of flight with the machine inverted.

REGION OF IMPOSSIBLE MANEUVER. - If the tail has a minimum setting, say $\alpha = -20^{\circ}$, the system of α curves is limited to this curve $\alpha = -20^{\circ}$.

If the center of gravity of the airplane is sufficiently forward between o" and o, there are no elevator settings which allow of finding a position of equilibrium at large angles of attack (greater than $i = 11^{\circ}$ for instance).

The ceiling of the machine is then determined by this maximum angle of attack compatible with the controls. The machine loses part of its flying qualities through being badly balanced.

If the machine should happen to be placed in such conditions of flight that its angle of attack exceeds $i = 11^{\circ}$, it cannot keep such a position and will nose dive until the maximum angle of attack compatible with its balance is reached.

In such a case, the machine has no maneuverability at large angles, while having excessive stability at small angles.

When the elevator setting is not limited by construction, the action of the controls is none the less limited for each value of i to a maximum setting such that $\alpha + i$ (Fig.6) is the angle at which the tail plane reaches its maximum K_y.

If we increase or reduce α beyond this value, the K_y of the tail plane decreases, and the action produced by the elevator is the reverse of what would be normally produced by a larger setting of the elevator.

Thus, even with an elevator which can be set to any angle, there is a limiting curve which, for a given center of gravity, determines a maximum angle of attack, beyond which the machine is unable to maintain its flight.

It should be noted that with elevators which can be set at any angle, it is possible to fly with the elevator set at an angle greater than that required for maximum efficiency, but in such a case the action of the controls is reversed.

The curves shown on Fig. 7 are those of a glider having a tail of small relative area, but altogether mobile; the figure shows that the curve $\alpha = 0^{\circ}$ and $\alpha = -3^{\circ}$ intersect each other, thus indicating that, for sufficiently large angles of attack the setting $\alpha = -3^{\circ}$ reaches and exceeds the setting required for maximum efficiency.

The foregoing remarks only apply to the longitudinal equilibrium of the glider, independently of the axis of thrust

of the propeller, drag, and available power. From these remarks it results that, with current wings and THE DISPOSITIONS OF TAILS USUALLY EMPLOYED;

1st. - MACHINES HAVING THE CENTER OF GRAVITY VERY MUCH FORWARD (in front of o") cannot fly at large angles of attack, and are consequently unable to reach the ceiling for which they are fitted by their aerodynamical characteristics.

Also, they can only land at small angles of attack, and their landing speed is, therefore, much too high.

These machines have far too much auto-stability at small angles of attack.

It appears from the system of curves shown on Fig. 1, that if we assume a minimum tail setting, $\alpha^m = -20^\circ$, the airplane will not be able to reach its angle of flight at the ceiling (this angle being about 12°) if its center of gravity, G, is at less than 1/4 of the chord of the wing from the leading edge, that is, between o" and o.

2nd. - MACHINES HAVING THE CENTER OF GRAVITY BETWEEN o' o" (ABOUT 1/3 OR 1/4 FORWARD OF THE WING) are stable at all angles of attack utilized in flight. They can be maneuvered at all angles up to the ceiling.

3rd. MACHINES HAVING THE CENTER OF GRAVITY TO THE REAR (AT ABOUT 1/3 FORWARD OF THE WING) AT o' FOR INSTANCE, are in neutral balance at normal angles of horizontal flight at a mean altitude.

These machines are dangerous to fly; when they are put to a nose dive, they continue diving by force of inertia without the controls being touched, and only right themselves when the pilot sets the elevator at the angle corresponding to equilibrium at horizontal flight.

In order to right them, the pilot must intervene energetically.

For the same reason, when these machines are tail heavy, they keep the same position.

These facts can easily be deduced from an examination of the curve $\alpha = 0^\circ$ (Fig. 1).

We shall assume the airplane to be balanced for flight, such balance being marked on the figure by the point ω, corresponding to $\alpha = -5^\circ$, $i = 11^\circ$.

If the pilot wishes to nose dive, he increases α. Suppose he takes $\alpha = + 5^{\circ}$; the machine will nose dive, and keep on diving up to -10°, if the pilot keeps the same setting.

Moreover, the machine will continue diving by the force of inertia, even though the pilot returns to the setting $\alpha = 0^{\circ}$ (the setting for normal flight).

As a matter of fact, with this setting, $\alpha = 0^{\circ}$, the variation of the angle of incidence from $i = 7^{\circ}$ to $i = 1^{\circ}$, causes no displacement of the center of thrust, and therefore no torque intervenes to fix the machine at a given angle of attack within those limits.

For certain gliders, the angle of attack may thus happen to be negative before we find on the α curve a point of equilibrium corresponding to a center of thrust further forward than G and creating a righting torque.

IT SHOULD BE NOTED (though it may seem rather paradoxical) THAT THIS DANGEROUS DEFECT OF NEUTRAL STABILITY ARISING FROM A CENTER OF GRAVITY PLACED TOO MUCH IN THE REAR, MAY, IN A FREE FLIGHT TEST, CAUSE A TENDENCY TO NOSE DIVE. THIS MIGHT LEAD TO THE FALSE ASSUMPTION THAT THE BALANCE WAS PLACED TOO FAR FORWARD.

These machines with neutral stability are particularly dangerous in the take off and may have a tendency to capsize instead of getting off the ground. I will return to this point later on.

4th. - MACHINES HAVING THE CENTER OF GRAVITY VERY MUCH TO THE REAR; BEYOND o'c (outside the forward 1/3 of the wing) are in unstable equilibrium at normal angles of flight at low altitudes; they are only stable at large angles of attack.

In flight at small angles, if the aviator accidentally points the machine up, it becomes tail heavy; if he accidentally points it down, it becomes nose heavy

These machines fly at small angles of attack with α generally positive (when the fixed plane is parallel to the wing): the tail has then lifting power.

In such machines, the controls are usually inverted only for negative angles of attack.

INVERTED FLIGHT. - The α curves plotted on Fig. 1 are discontinuous.

The discontinuity corresponds to the actions of the air, and the general sweep of the curves at negative angles indicates that the conditions of good balance are of the same nature in flight in an inverted position as in normal flight.

EFFECT OF THE POSITION OF THE AXIS OF PROPELLER THRUST.

RELATIVE POSITION OF THE AXIS OF THRUST AND OF THE CENTER OF GRAVITY. - In the first part of the Paper we assumed that the machine was one with coinciding centers, that is, that the center of gravity was on the axis of propeller thrust.

The component of the total resultant of the actions of the air, we have called resistance to thrust, as opposed to the thrust of the propeller, when the other component is vertical.

Practically, there are no machines with exactly coinciding centers. The center of gravity is always either above or below the axis of thrust.

In studying the stability of a machine having exactly the same glider as that considered in the first part of this Paper, but having its center of gravity G not placed on the axis of thrust, we can utilize the same curves, on condition of considering, not the position of G, but the position of g, the point at which the vertical passing through the center of gravity meets the axis of thrust (Fig. 8).

The result is that g is not fixed on the axis of thrust as G was.

g moves one way or the other when the angle of attack varies, according to whether G is above or below the axis of thrust.

We are still only considering a rectilinear regime of flight where the forces are in equilibrium.

In such a case, whenever g is in the region of good stability, the machine is stable, whatever be the position of G with respect to the axis of thrust.

Machines in which the center of gravity is not near the axis of thrust, thus always possess a region in which the angles of attack correspond to good stability.

MACHINES IN WHICH THE CENTER OF GRAVITY IS BELOW THE AXIS OF THRUST. - For these machines, the imaginary center of gravity g moves backwards when the angle of attack decreases and forward when it increases (Fig. 9).

Therefore if the balance is good at mean angles, there is a region of instability at small angles and a region at large angles of attack in which no maneuver is possible.

The displacement of g therefore presents an inconvenience in each particular case. At small angles of attack the machine becomes distinctly unstable, and has no maneuverability at large angles (if the center of gravity is sufficiently below the axis of thrust).

This case of defective balance may especially occur on seaplanes with hulls. Its importance evidently depends on the glider used in each particular case, for, as we shall see, the α curves depend on all the constituent elements of the glider.

MACHINES IN WHICH THE CENTER OF GRAVITY IS ABOVE THE AXIS OF THRUST. - In these machines the imaginary center of gravity g moves forward when the angle of attack decreases, and backwards when it increases.

Therefore, when balance is good at mean angles, the machine, owing to the form of the curves, will be stable at large angles, although balance is to the rear, and will have maneuverability at small angles of attack like all machines having balance forward.

It thus appears that from the point of view of stability in rectilinear and uniform flight, there is a decided advantage in having the center of gravity above the axis of thrust. The distance between them must not, however, be too great.

RELATIVE POSITION OF THE AXIS OF THRUST IN THE GLIDER.-

There is another reason why the position of the axis of propeller thrust is of so much importance in balance, and that is its relative position as affecting the whole of the glider.

In fact, the whole study is so far based on the displacement of the point of intersection OF THE RESULTANT OF THE REACTIONS OF THE AIR AND THE AXIS OF THRUST. Considering that this resultant varies in direction with the angles of attack, it follows that the displacement of the point of intersection will be more or less, according to the position of the axis of

propeller thrust.*

This appears clearly on Fig. 10, which gives a metacentric sheaf corresponding to a given setting of the elevator.

The points of intersection of the different resultants with a given axis of thrust will define the abscissas of the α curve studied above as function of the angles of incidence.

It further appears (Fig. 10) that the lower the axis of thrust in the glider, the slighter the relative slope of the α curves.

The elevator has therefore become more sensitive, and the region in which the balance is considered to be good, o'o", is enlarged; the machine is more easily balanced and the operation is not so delicate.

If, on the contrary, the axis of thrust is raised in the glider, the center of thrust will vary much less for the same variations in the angle of attack, and hence the α curves have a much steeper slope. Consequently, the machine does not answer so readily to the action of the steering mechanism, and the region of good balance, o"o', is greatly reduced; all this necessitates extreme accuracy in construction if the machine is to have stability and maneuverability.

If the axis of thrust is raised still higher in the glider, if, in particular, it is in the vicinity of the metacenter corresponding to the case under consideration, stability will be neutral in the vicinity of the setting α and of the angle of attack which determines this metacenter.

For values of α or i corresponding to metacenters above the axis of thrust, the elevator regains a little efficiency. For values of α and i corresponding to metacenters below the axis of thrust, the machine will be unstable, for the corresponding α curves will slope in the contrary direction to those we have hitherto considered in the region of stable equilibrium.

We thus see that the position of the center of gravity with respect to the axis of thrust, and the relative position of the axis of thrust in the glider are of the greatest importance in the balance of an airplane.

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* It should be understood that we assume (which is not exactly the case) that the axis of thrust can be displaced in the glider without affecting the magnitude and position of the passive resistances and hence without affecting the magnitude and direction of the general resultant of the actions of the air.

If it is desired to have a very stable machine, the axis of thrust must be placed low in the glider; it may then be below the center of gravity and will thus, for two reasons, facilitate good balance.

The position of the axis of thrust in the glider is often decided by questions of construction or of practical use. In certain seaplanes such considerations lead to the axes of thrust being placed very high in the cellule; in such cases careful experiments should be made in the wind tunnel in order to find out whether this position of the axis of thrust renders it impossible to have a machine which is automatically stable at normal angles of attack. In cases where the machine is found to be still automatically stable, these tests would determine the exact region in which the vertical of the center of gravity must remain in order that the machine shall be stable and controllable at all angles of attack which it can utilize.

INITIAL ADJUSTMENT OF THE TAIL PLANE.

The glider hitherto considered was that having a tail formed of a fixed plane and an elevator.

Since the object of the latter is to vary, by its setting α the K_y of the whole tail, it is evident that the form of the α curves will depend on the ratio of the area of the elevator to that of the fixed plane. The argument, however, is not affected, whatever this ratio may be; the same general sweep of the curves is kept, even though the whole tail plane is flexible. Figs. 7, 11, 12, are those of tails which are entirely flexible.

If the elevator has a fixed part and a flexible part, as on the glider hitherto considered, it is well to adjust the fixed part so that, in horizontal flight at the normal altitude of utilization, the flexible part of the tail plane shall be in the bed of the wind, thus causing no fatigue to the pilot.

The best solution is evidently to have a fixed plane which can be regulated from the pilot's seat, so that this reduction of fatigue may be realized for all regimes of flight which can be utilized.*

For machines in which the fixed part of the tail plane cannot be regulated, it should be initially adjusted so that, at the angle of flight at the altitude considered, the

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* British Transport Planes especially have been designed with this idea. Several interesting devices were shown at the last French Aeronautic Show.

elevator being in the prolongation of the fixed plane, the whole of the tail shall be set so that the center of thrust is on the vertical of the center of gravity.

Tests have been made under these conditions for the glider considered, with tails of various shapes and dimensions.

The curves of these tests have already been given in Figs. 7, 11, and 13. By these curves we see that, when the whole tail plane is flexible, the phenomenon is exactly comparable to that studied in the case where only the elevator was flexible.

From the curves shown in Figs. 7, 11, and 12 we may conclude that, for a given glider flying at a given altitude at an angle i_o, the machine being all the more stable at the center of gravity is further forward, the tail plane will have a negative adjustment with respect to the chord of the wing, and this negative adjustment will be greater as the machine is more stable**.

Stability at a normal regime of flight at a normal altitude will thus be usually characterized by the upward V formed by the chord of the wing with the chord of the tail plane.**

Machines adjusted with a downward V (lifting tail) will be very near instability, and will assuredly be unstable at small angles of attack.**

**

We are led to these conclusions by considering that, in order to keep the equilibrium of forces we must, in advancing the center of gravity, set the tail so that it will lose lift to such an amount that the righting torque created equilibrates the diving torque due to the new position of the center of gravity

THESE CONCLUSIONS ARE ONLY ABSOLUTE FOR SYMMETRICAL EMPENNAGES; WE MAY, IN FACT, CONCEIVE OF TAIL PROFILES (INVERTED WING PROFILE) SUCH THAT THE TAIL HAS NO LIFT THOUGH ITS CHORD DOES NOT FORM A V WITH THE CHORD OF THE WING. There would be great advantage in studying such tail shapes, the use of which might considerably modify the sweep of the curves and reduce the head resistance of the empennages while keeping and even increasing their efficiency.

In particular, we may see the possibility, with such tails, of balancing airplanes, without any ill effects, more to the rear than is done on our present machines.

STABILITY AT THE START.

In this Paper we have stated that an airplane balanced too far back, and consequently, almost neutral as to stability, has a tendency to capsize at the take off.

In order to prove this tendency, we will begin by determining the best position for the landing gear, that is, the position of offering the greatest safety, both when the machine is running along the ground, with its skid down, after landing, and when it is taxi-ing along, tail up, before taking off.

Many authors advise the adoption of a large ground angle, that is, to place the landing chassis in such a way that the wheels touch the ground very far in advance of the center of gravity.

According to these writers, this ground angle should be about 20° when the machine is in the line of flight, hence, about 35° when the skid is on the ground.

This would allow the airplane all safety of movement on the ground after landing when the skid is on the ground.

The large ground angle makes the machine tail heavy and the skid therefore acts as a strong brake. An angle of 35° would, however, seem excessive.

An incautious increase of this ground angle can only give rise to inconvenience, and that, for two reasons:

First, because it will make the machine more likely to run crooked when rolling along with the skid on the ground, and also because it decreases stability at the take off and increases the chance of the machine capsizing, as will be shown later.

Without taking into account the position of the axis of thrust, let us assume that the airplane has coinciding centers and that, although the wheels are on the ground, a uniform regime is established for a very short time, the machine being in the line of flight (Fig. 13).

Consider the equilibrium of the forces when the airplane has a large ground angle, the wheels touching the ground greatly in advance of the center of gravity G:

The machine is then maintained in the line of flight by the action of the elevator set at $\alpha = + x$, so that at small angles of attack the center of thrust for the whole of the glider is sufficiently far back to ensure the moment of the reaction

to lift with respect to the center of gravity, equilibrating the moment of the reaction of the wheels with respect to the same center of gravity. The reaction of the ground on the wheels is not normal to the ground, it has a horizontal component equal to the product of the vertical component and the coefficient of friction of the wheels on the ground.

The total resultant is thus slightly inclined to the rear; it nevertheless passes in front of the center of gravity of the machine, so that, in order to balance it, the thrust due to the actions of the air must, on the contrary, pass to the rear of this center of gravity.

The result is that if the machine is normally balanced very far back, the center of thrust at the take off will very probably fall on the sheaf of α curves corresponding to unstable balance.

In this case if, for any reason the machine begins to point up, it will continue in that position unless the pilot acts on the elevator, but finds a position of equilibrium when the righting torque of the actions of the air balances the carrying torque of the wheels, the moment of which has always a maximum.

If, on the contrary, the machine begins to point down the center of thrust moves rapidly backwards and the machine continues nose diving. The reaction torque of the wheels, which might oppose this movement, does not necessarily increase, for though the reaction of the ground may increase, its lever arm decreases owing to the change in the direction of the airplane.

Under these conditions the machine will most usually capsize before the pilot has time to intervene.

When the wheels touch the ground near the vertical of the center of gravity, the position of the center of thrust corresponding to balance also approaches G and may be in the region of good stability.

It is perfectly clear that only airplanes having the center of gravity very much forward can tolerate a large ground angle, and the further back the machine is balanced, the greater must be the reduction in the ground angle.

We have examined the question of stability of balance without mentioning the causes which may disturb it. One of these causes is the ground, the inequalities of which may increase or reduce the reactions on the wheels and change their direction.

For instance, an inequality of the ground which increases the reaction, generally inclines it, at the same time, further to the rear.

If the inequality of ground increases the torque due to the wheels, the machine will point upwards and the angle of attack increases, but if the center of thrust is in a stable region, it moves backwards and will again find a position of balance. When the effect of the inequality ceases, the machine will resume its position.

If the inequality of ground reduces the torque due to the wheels, the airplane points downwards, the center of thrust moves forward if it is in a stable region and recovers a position of equilibrium.

In short, when the actions of the air are sufficient, when the airplane can taxi along in the line of flight, for instance, a large ground angle does not increase safety, but, on the contrary, reduces it.

Machines balanced too much to the rear are, generally, unstable at the take off and have a special tendency to capsize; this tendency increases with increase of the ground angle.

Even for well balanced machines, it is better to have a small ground angle when the airplane is in the line of flight, 3 to 5°, so that, when the skid is on the ground we shall have a ground angle of 15 to 20°, sufficient for taxi-ing with safety.

The ground angle required for the airplane to run along the ground, skid down, may be still further reduced if there are emergency wheels in front to check any tendency to capsize on a poor terrain.

INFLUENCE OF WING PROFILE AND OF PASSIVE RESISTANCE.

The system of curves on which this whole discussion is based correspond to a given glider. If the general configuration of the glider be modified, the sweep of the curves will be appreciably altered.

We have already shown that the position of the axis of thrust in the glider has a fundamental influence on the general sweep of the α curves.

It is also quite natural to assume that the α curves will change their sweep if the profiles of the wings and tail planes change or if the shape or relative position of the constituent elements of the glider varies (fuselage, landing gear,

floats, rigging, etc.). The aerofoils and these elements are, in fact, subject to actions of the air (individual or interferential actions) the sum of which defines the magnitude and direction of the total resultant, and, therefore, the position of the center of thrust the displacement of which we have been studying.

The approximate law of balance which fixes the center of gravity between the forward 1/3 and 1/4 of the wing is thus not sufficiently precise to be utilized in all cases without being checked. And when an inventor adopts new arrangements affecting the shape or position of the wings and fuselages, he must, as when he places the axis of thrust in extreme positions, have recourse to wind tunnel tests in order to determine the particular balance curves of his machine and the best relative position of the center of gravity with respect to the wings.

INFLUENCE OF THE STEERING MECHANISM.

Each constituent element of the glider has a greater or less share in determining the law of displacement of the center of thrust in the ensemble. In the present state of our aerodynamical knowledge, however, it seems very difficult to distinguish clearly the part taken by each.

We will endeavor to indicate the sense of the individual action of certain parts (more especially of the steering mechanism) on the displacement of the total center of thrust of the machine, and to find out what important factors of equilibrium may vary with the dimensions, shapes, and relative positions of such steering mechanism.

The torque resulting from the actions of the air on the steering mechanism may be reckoned, a rough approximation, as being proportional to the surface of the tail s for a cellule of given area S.

It may also be considered as practically proportional to the length of the relative lever arm, that is, for a given depth of wing l, and a distance L from the center of thrust of the tail to the center of total thrust, proportional to L/l.

We may thus write this torque in the form:

$$A \frac{s}{S} \times \frac{L}{l}$$

The coefficient A depends on the profile of the tail planes, that is, on the value of K_y, on the mean velocity V' of the airstream in which the tail plane finds itself when the speed of the cellule is V, and lastly, on the relative direc-

tion of the air filaments about the tail (a direction which differs from that of the initial airstream on account of the deviation of the air filaments produced by the planes of the cellule).

Briefly, we may represent the relative action of the elevator by an expression of the form:

$$A_1 \, K_y \, \frac{V'^2}{v^2} \times \frac{s}{S} \times \frac{L}{l}$$

K_y varies with α according to the tail profile adopted and with the angle of attack of the tail.

V' always less than V, varies with the drag of the molecules of air along the fuselage preceding the tail.

Experiments made in the Laboratory seem to indicate that the airstream along the fuselage may slow down by about 20%.

This loss of velocity is certainly due to the forms of the fuselage and must increase with its length.

It must also depend on the angle of attack, since the relative displacements of the bodies masking the tail planes correspond to variation in the angle of attack.

On actual machines s/S and L/l vary rather slightly. The product $S/s \times L/l$ has a value of the order of those given below:

AIRPLANES	: s/S	: L/l	: $\frac{s}{S} \times \frac{L}{l}$
BREGUET 14 A2	: 0.12	: 3.01	: 0.362
SALMSON 2 A2	: 0.106	: 3.33	: 0.354
FARMAN 50 Bn2	: 0.0905	: 2.94	: 0.266
CAUDRON 23 BN2	: 0.106	: 3.12	: 0.33
SPAD 13 C 1	: 0.134	: 2.73	: 0.366
S.E.A. 4 C 2	: 0.1016	: 3.22	: 0.327
FOKKER D 7 C 1	: 0.1276	: 3.10	: 0.396
HENRI-PAUL Bn2 (the glider studied)	: 0.100	: 3.26	: 0.326

The variations of the product $\frac{s}{S} \times \frac{L}{l}$ must have a combined action on the α curves, displacing them in relation to the wing, moving them backwards when the product diminishes, and forward when it increases. These variations must also act on the relative spacing of the curves and on their slope with respect to the axis of the thrust.

By varying this product it should therefore be possible to enlarge the region of good stability and thus make it easier to balance the machine.

This appears by a comparison of Figs. 7 and 12, which correspond to gliders having monoplane tails of different areas.

It should, however, be noted that this product s/S x L/l cannot be indefinitely increased, for this involves an increase in the weight and dimensions of the fuselage, and this is often incompatible with the laws of good construction and with the conditions of form essential to the tail and fuselage. We further note that the relative variations of L can only be small, and experience shows that the gain obtained by the increase of L/l tends rapidly towards zero.

This may be partly explained by the decrease of V' which inevitably results from the increase of L, and which produces a result the contrary of that sought.

The variations of the ratio V'/V have the same influences as those of s/S and L/l.

Therefore, in each particular case it is of advantage to adopt the arrangement of tail planes for which this ratio is maximum and for which the elevator action is the most efficient.

The best position of tail planes is, of course, found outside the wake of the fuselage in regions where V' is practically equal to V; this is partly realized for the upper part of biplane tails and for the tails of machines having connecting beams.

In point of fact, the position giving the best ratio V'/V is not the same for all cases of flight. This ratio varies with the angle of attack at which the machine is flying.

In flight at small angles, the monoplane tail is in the wake of the fuselage and has, therefore, a poor V'/V; while at large angles it has only a small part of the fuselage in front of it and again has a very good V'/V.

On the contrary, the biplane tail has a better V'/V at small angles and a poorer one at large angles.

On the α curves this is marked by a variation in the curves, the α curve of the biplane tail having the least slope at small angles of attack, and the monoplane tail having the least slope at large angles.

This appears clearly on Fig. 14, where the displacement of the curves may be attributed to difference of tail area, but where the variations of curvature are to be imputed to the difference in the kind of tail adopted.

Lastly, the ratio of the flexible to the fixed parts and the tail profile have an influence which combines with that of the wing profile to give the α curves their general sweep.

If the tail is biplane, the influence of the interaction of the planes and that of the supplementary passive resistances diminish its fineness ratio and thus partially reduce the gain which might have been hoped for from the increase of V'/V.

SENSITIVENESS OF THE AIRPLANE TO THE ACTION OF THE STEERING MECHANISM:

We will define the sensitiveness of the glider to the action of the steering mechanism by the relative magnitude of the displacement of the center of total thrust corresponding to a given variation of the setting for a given angle of attack.

Given the general sweep of the α curves, the airplane is more sensitive to the action of the steering mechanism as the α curves are relatively further apart and as their slope is less pronounced.

Summarizing the foregoing remarks, we may conclude that the sensitiveness of the machine depends:

1st. On the position of the center of gravity which defines the region in which these curves are utilized at normal regimes.

2nd. On the position of the axis of thrust in the glider, the form of the α curves varying with this position.

3rd. On the ratios s/S, L/l, V'/V.

4th. On the polars of the wings of the cellule, and ON THE TAIL PLANES.

5th. On the ratio of the fixed and flexible parts of the tail plane.

Considering the multiplicity of causes, we can see how difficult it is to analyze the phenomena observed in each particular flight.

In our opinion, it is indispensably necessary to have wind tunnel tests made for each case, giving the curves on which the balance of the machine can be based.

A discussion of this kind is only useful as it serves to give a rational direction to research work and to indicate the modifications in the parts of the glider which are the most likely to lead to the desired results.

For instance: it should be noted that for monoplane tails, considering the influence of V'/V, there will generally be every advantage in making them with a large span and small depth.

This fineness ratio should be carried as far as the possibilities of solid, rigid construction permit.

EQUILIBRIUM OF FORCES.

All the preceding conclusions have been obtained by studying the relative position of the forces concerned, without taking into account the order of magnitude of these forces.

Hence, the stability of the glider has only been studied as regards movement about the center of gravity, taking as reference direction that of the relative velocity of the air without considering climbs or loss of altitude which may result from the maintenance of balance; these considerations may, however, be of vital importance in certain conditions of flight, in particular, in flight near the ground.

In order to render this discussion complete, we must consider the other equations of flight, and in particular the equation of lift and the equation of power. Here also we will assume that there is an established regime, namely, that of a horizontal flight uniformly rectilinear.

Comparing at a given altitude (Fig. 15) the power required and the power available for horizontal flight at a given altitude (consequently at a given angle of attack) it is easy to see what are the conditions of equilibrium of these two powers, and, hence, of the stability of the corresponding regime.

If we fix the throttle setting, we dispose, according to the efficiency of the propeller (which itself depends on the speed of displacement V), of a power of thrust represented in function of this speed V by a curve T'a altogether below

the curve Ta which represents the maximum power available at full throttle,

The curve T'a intersecting the curve of required power at two points, L and R, only two regimes of flight are possible at the altitude considered. The regime marked by L is that of slow flight; it marks the lowest speed at which, with the throttle adopted, the machine can keep at the altitude considered. The point R marks the high speed regime usually employed.

Slow flight is obtained with a large angle of attack, high speed with small angles.

We have shown that at large angles of attack, the glider considered alone was in stable equilibrium, whatever might be the balance of the machine, provided that the elevator was efficient.

In flight at large angles of attack the equilibrium of forces is, on the contrary, unstable, On Fig. 15 it can be seen that if, at point L there is an accidental reduction of available power, the machine is subjected to drag and its speed decreases. Now, at a lower speed it must have a larger angle of attack in order to keep the same altitude. From this increase in the angle of incidence comes an increase in the power required for the flight, augmenting still further the initial conditions in which the forces are not in equilibrium. This regime is therefore dangerous in flight near the ground.

As a matter of fact, if the pilot does not touch the elevator, the machine, having stability of form, begins to descend, keeping, with respect to its line of flight, the angle of flight corresponding to the setting of the elevator.

Thus, by the action of gravity, the power required is found during the descent.

If, on the contrary, the pilot does not wish to descend on account of the configuration of the ground, and makes the mistake of pulling the stick in the hope of keeping his altitude by increasing the angle of incidence, he adds to the conditions in which the forces are not in equilibrium and comes down still more rapidly.

At high speed regime (angles of attack smaller than the angle of minimum power required), the glider is stable, that is, it keeps a determined position with respect to the relative velocity of the airstream, provided that the center of gravity is not too far back.

The equilibrium of force is then stable also in horizontal flight, and in studying a case similar to that at L, we remark at the point of equilibrium R, that if there is a reduction of available power, the result is such a decrease of speed that, at the altitude considered, the required power is reduced even more than the power available, so that the flight continues with excess power and the variations in power are such that they act against the accidental conditions in which the forces are not in equilibrium.

In any case, the pilot can be sure of keeping his altitude by a maneuver which will counterbalance the accidental variation of the angle of attack.

At the altitude considered, he is safe so long as the power available is greater than the minimum of power required for flight at that altitude.

To sum up: if we consider only machines with coinciding centers:

For small angles of attack: airplanes having the center of gravity too far back are unstable from the fact that variations in the position of the center of thrust caused by disturbances which produce elementary variations of the angle of attack.

Airplanes in which the vertical of the center of gravity falls in the forward 1/3 of the wing are stable, and their stability is greater as the center of gravity is further forward. These machines are very sensitive to elevator action at small angles.

The angle of flight being less than the angle of minimum power, the equilibrium of forces is stable in horizontal flight.

For large angles of attack greater than the angle of minimum power required for flight at the given altitude, the regime of horizontal flight is unstable, owing to the instability of the equilibrium of available and required power, whatever be the balance of the machine.

Still, planes balanced to the rear have, generally, at these large angles, a stable glider, that is, which has an automatic tendency to keep the same angle of attack with respect to the relative airstream; while machines balanced forward have the glider non-maneuverable and incapable of finding equilibrium in flight owing to the insufficiency of its steering organs. In point of fact, the latter defect gives relative safety, since it makes low speed impossible.

In discussing the stability of the equilibrium of forces, we have not brought in the position of the axis of thrust with respect to the center of gravity of the machine. A few remarks should be made on this subject.

The variations of power may produce accidental conditions in which the forces are not in equilibrium between the propeller thrust and the resistance of the air to thrust. What may be the effect of such conditions in which the forces are not in equilibrium on the machine?

For a plane having its center of gravity below the axis of thrust, if the thrust increases the machine tends to dive; if thrust decreases, it has a tendency to point upwards. Both these tendencies are usually contrary to the wish of the pilot, who, normally, accelerates the engine for climbing and reduces the throttle for a descent.

Still, these tendencies correspond to the maneuvers which have to be made at high speed regime in order to keep the same altitude in spite of variations of power.

For a machine having its center of gravity above the axis of thrust, if thrust increases the machine has a tendency to point upwards; if thrust diminishes, the tendency is to point downwards. The tendencies of the machine combat the accidental conditions in which the forces are not in equilibrium of the powers and also normally correspond to the reflex maneuvers which the pilot must make for ascending or descending.

CONCLUSIONS.

We have indicated the multiplicity of elements involved in the equilibrium of an airplane, the variation of which usually defines the conditions of balance which must be realized.

The choice of the wing profile is generally decided by aerodynamical considerations and corresponds to the performances which the constructor wishes to obtain.

On the other hand, the position of the axis of propeller thrust is determined by structural considerations and according to the use for which the machine is intended; nor, generally speaking, can this position be varied to any appreciable extent. It should, however, be placed as low as possible, having regard to the conditions arising from the type of machine to be built.

We also stated that the length of the fuselage is

fixed to within very slight variations, practically without influence.

Therefore, for improving the balance of an airplane, we can alter:

1st. The position of the center of gravity.

2nd. The dimensions of the tail.

3rd. The profile of the tail.

4th. The position of the tail planes.

By making wind tunnel tests on the glider with different tails, it is possible to determine what tail arrangement, having regard to the axis of thrust, will give the system of α curves affording the most extensive region of good balance.

In this region should be placed the center of gravity.

Unfortunately, the position of this center of gravity is also affected by considerations of construction and load, and it can only be varied within extremely narrow limits, even on model machines.

In serial machines, tolerances of construction may so greatly modify the position of the center of gravity as to render the balance of one machine very different from that of its neighbor.

Therefore, in order to be able to give good balance to each particular machine, it is absolutely necessary to allow a certain amount of tolerance in construction so that large masses may be displaced by a few centimeters.

For instance, we should be able to displace the fuselage with respect to the cellule (small variations of L are of no importance) or, in multimotors with lateral beds, we should be able to slightly change the position of the engines in the beds.

Since such possible displacements will generally be very small, we see the great advantage of BASING THEM ON WIND TUNNEL TESTS.

These tests will enable us to find the general arrangement of glider offering the best guarantees of stability, sensitiveness, and maneuverability.

POSITION OF EVENTUAL LOAD. - The load of the airplane may change, as also the weight of fuel it carries.

Therefore the elements of this load and the gasoline tanks must be so placed that any loss of weight in them will not injure the stability of the machine.

In the first place, they should be placed as near as possible to the center of gravity.

In the second place, if the machine is well balanced with a full load, the weights which may vary should preferably be placed to the rear of the center of gravity, so that a lightening of weight will throw the total center of gravity further forward, thus increasing stability.

In placing such weights as tanks, bombs, or mail bags too far to the rear of the center of gravity, we fall however, into another error, for the lightened airplane will be balanced too far forward and will only be able to land at a small angle of attack involving too high landing speed.

If the machine is balanced forward when loaded, the variable masses may be in advance of the center of gravity; the lightening of the machine will allow it to land at a larger angle, that is, at a lower speed, without any injury to its stability.

We must again repeat that the really unstable machines are those having the center of gravity too far back, or the axis of thrust placed too high in the glider.

Machines having the axis of thrust too high may be completely unstable at normal regimes of flight; they will fly better inverted than in a normal position.

The wheels should be placed slightly in advance of the center of gravity, but when the machine is in the line of flight the ground angle need not be more than a few degrees. For airplanes having the main wheels on the vertical of the center of gravity, an auxiliary set of wheels may be placed in front of them in order to increase safety; these will prevent the machine capsizing when maneuvering on the ground at reduced speed. These extra wheels should not be usually employed in taking off and landing; they will only touch the ground in case of an exaggerated nose dive.

Lastly, we can only once more urge airplane manufacturers to interest themselves very especially in wind tunnel tests.

These tests may not always give satisfactory quantitative results, but they will always give the sense of the

variation of effects, they will determine causes and will serve as a sure guide to the seeker, who would otherwise wander blindly; his work would certainly suffer if he neglected to guide himself by well thought out tests on reduced models of his machine.

Translated from "La Vie Technique & Industrielle," 1920, by the Paris Office, N. A. C. A.

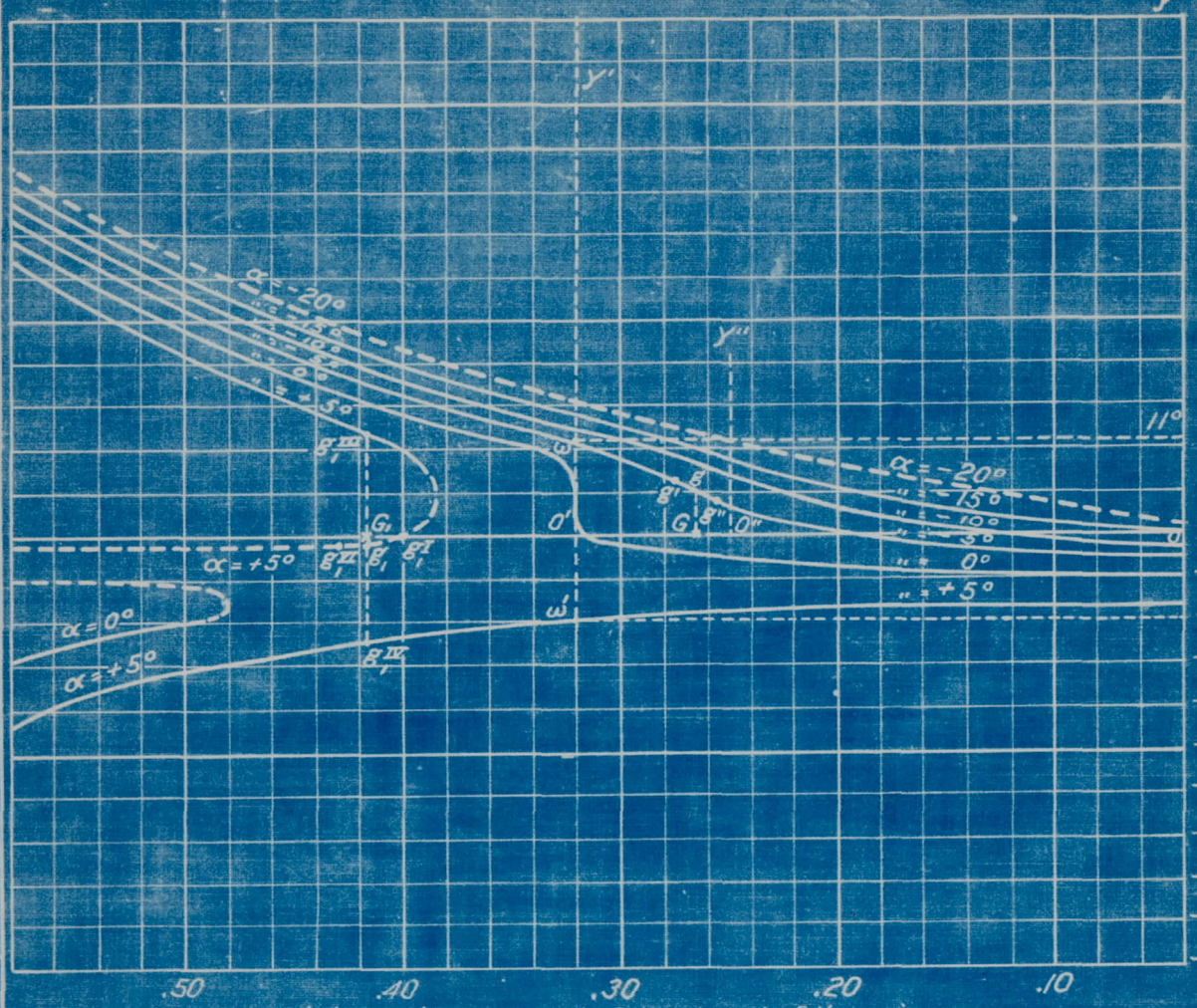

Fig. 1

Distance in per cent of the chord of the wing from the plane passing through the leading edges of the wings.

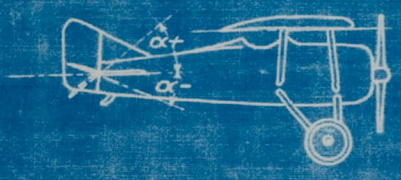

Fig. 2

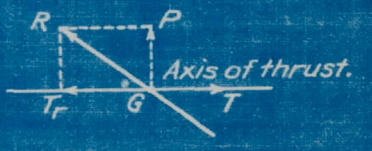

Fig. 3

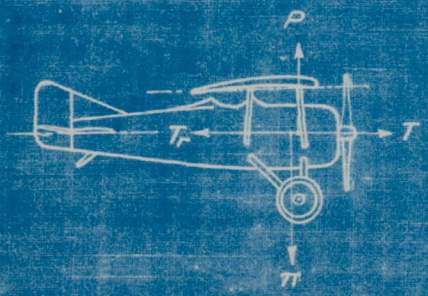

Fig. 4

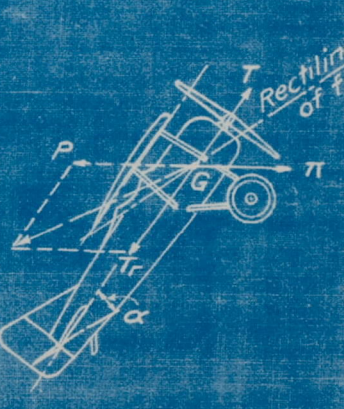

Fig. 5

Figs. 1, 2, 3, 4 & 5

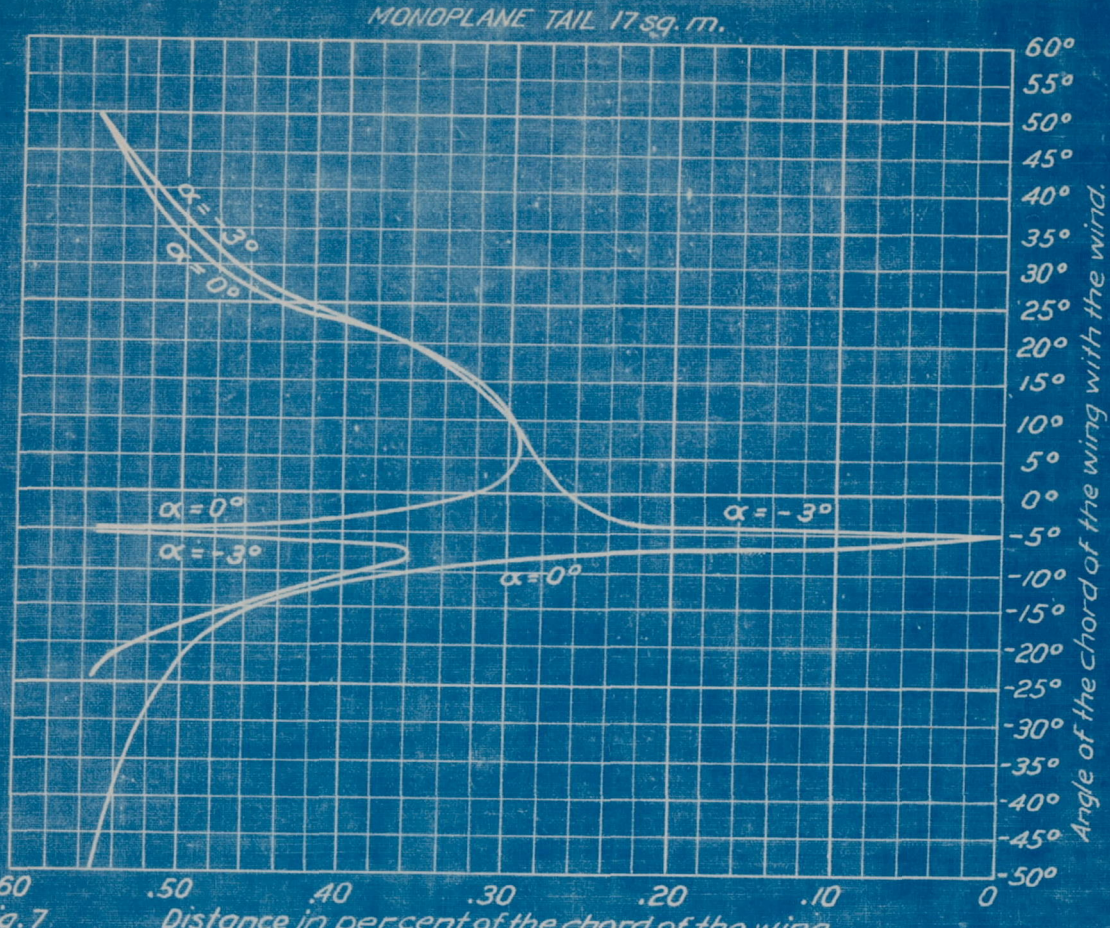

Fig. 7

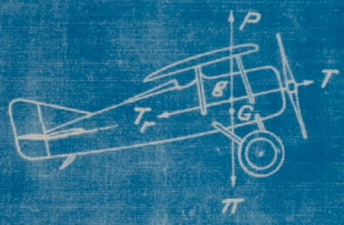

Fig. 8

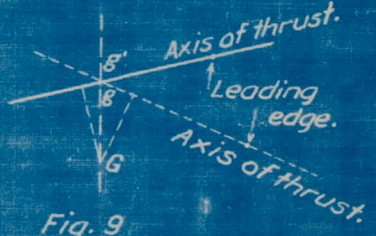

Fig. 9

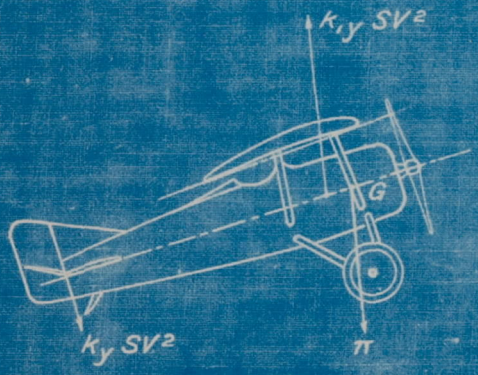

Fig. 6.

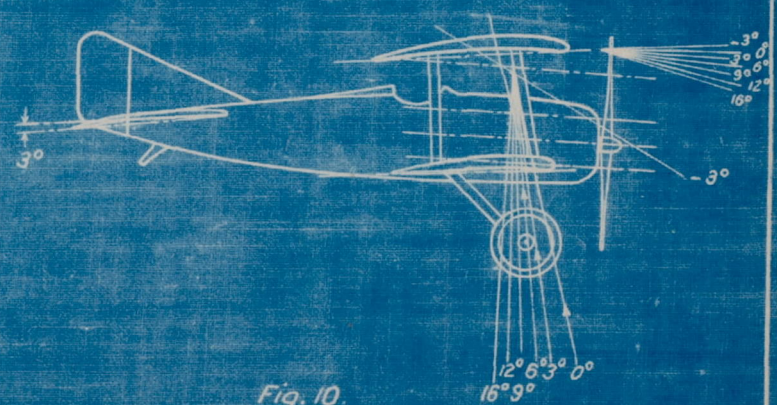

Fig. 10.

Figs. 6, 7, 8, 9 & 10

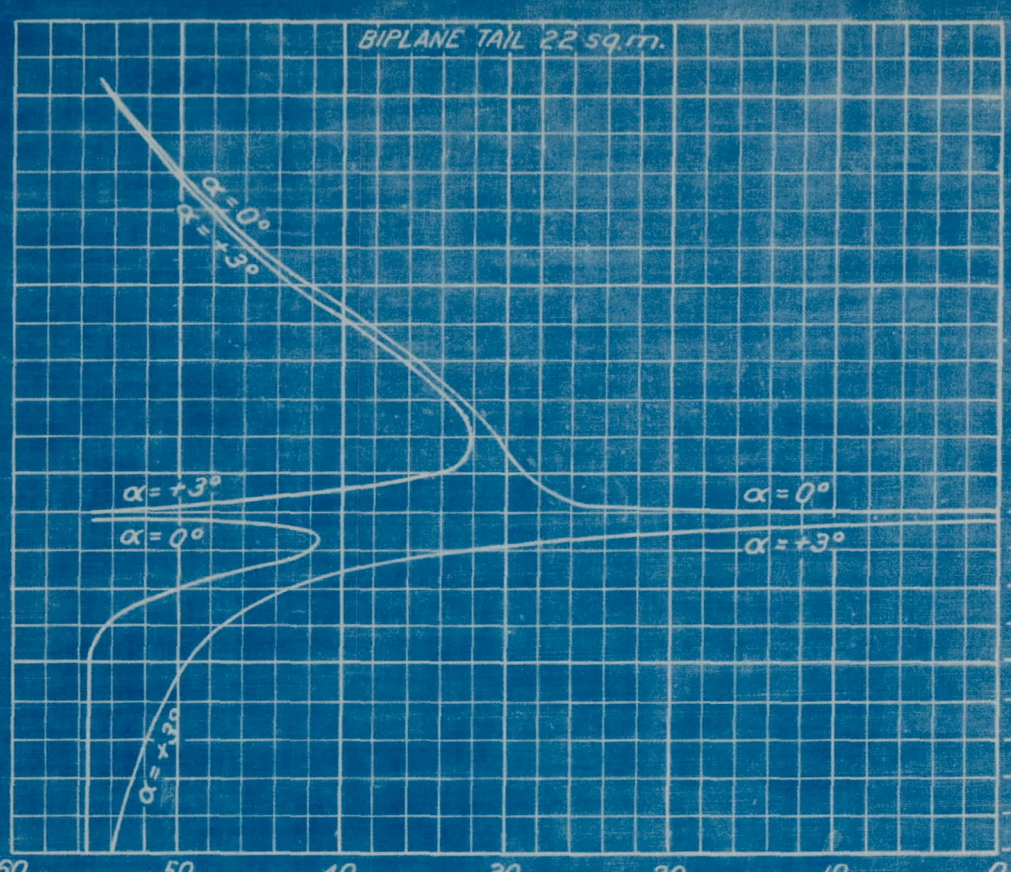

Fig. 11 Distance in per cent of the chord of the wing from the plane passing through the leading edges of the wings.

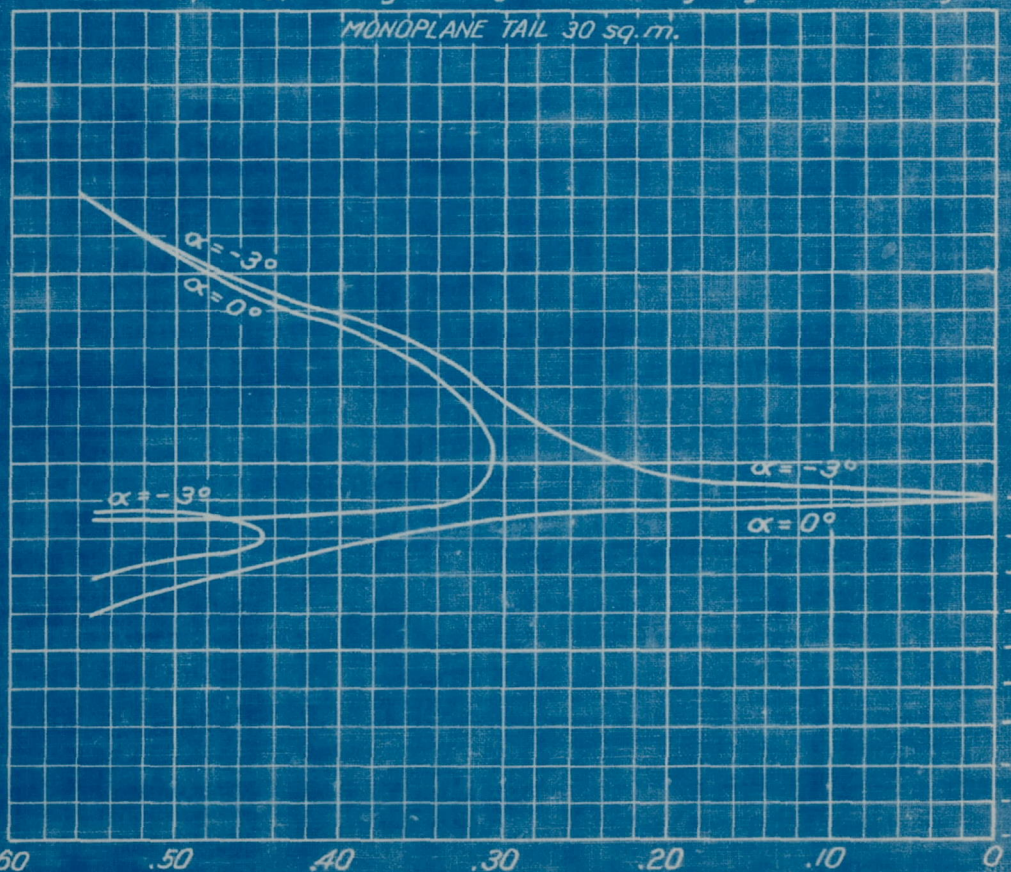

Fig. 12 Distance in per cent of the chord of the wing from the plane passing through the leading edge of the wing.

Figs. 11 & 12

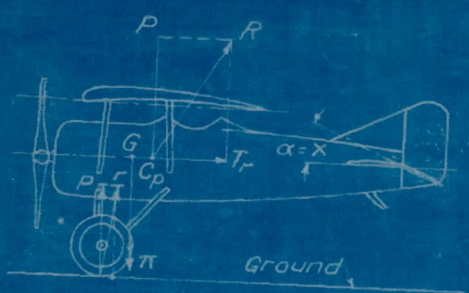

Fig. 13

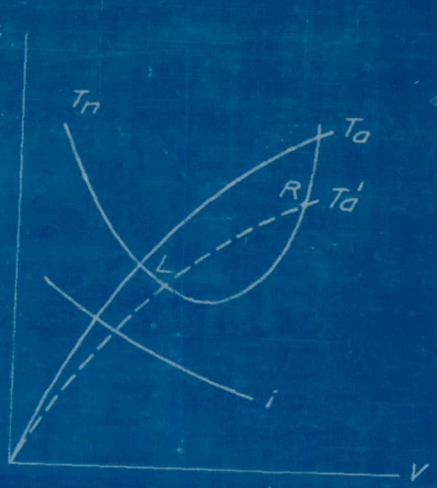

Fig. 15

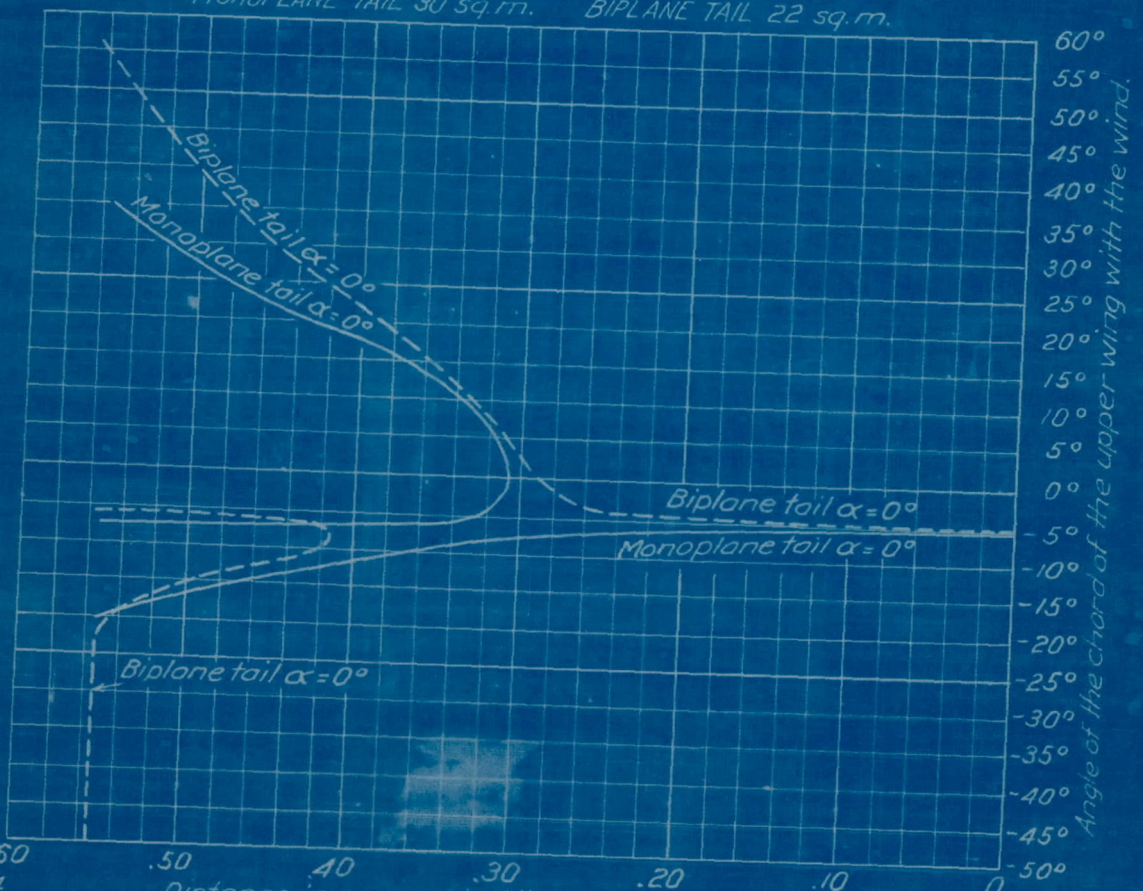

Fig. 14.